

BIBLIOGRAPHIC REQUEST FORM

Borrower's
Name

Cephia Toomer

Org. or
A.U.

1111

Phone

308-2509

Serial
Number

08/786,360

Date of
Request

10-3-97

Date
Needed By

ASAP 10-8-97

Please Attach Copy Of Abstract, Citation, Or Bibliography, If Available. Please
Provide Complete Citation. Only One Request Per Form.

Author/Editor:

Journal/Book Title: Wear

Article Title: Improvement in tribological properties of Chromium

Volume (Issue): 160(1) 181-4

Pages:

Year of Publication: 1993

Publisher:

Remarks: ISSN: 0043-1648

STIC Use Only

Accession Number:

193223

MUTS

LIBRARY ACTION	LC		NAL		NIH		NLM		NBS		PTO		OTHER	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Local Attempts														
Date														
Initials														
Results														
Examiner Called														
Page Count														
Money Spent														

Provided By: Source and Date

10/6/97

Ordered From: Source and Date

Remarks/Comments

1st & 2nd denotes
time taken to a
library

O/N - Under NLM
means Overnight
Service

FX - Means Faxed to
us

WEAR

*An International Journal on the Science and
Technology of Friction, Lubrication and Wear*

Volume 160 (1993)

Editor

D. Dowson (*Leeds, UK*)

Editorial Board

E. R. Braithwaite (*London, UK*)
T. H. C. Childs (*Leeds, UK*)
H. Czichos (*Berlin, Germany*)
N. Gane (*Preston, Australia*)
W. A. Glaeser (*Columbus, OH, USA*)
M. Godet (*Villeurbanne, France*)
H. E. Hintermann (*Neuchâtel, Switzerland*)
K. L. Johnson (*Cambridge, UK*)
J. K. Lancaster (*Marton-cum-Grafton, UK*)
K. C. Ludema (*Ann Arbor, MI, USA*)
D. A. Rigney (*Columbus, OH, USA*)
T. Sakurai (*Tokyo, Japan*)

Improvement in tribological properties of chromium oxide coating at high temperature by solid lubricants

G. H. Liu, F. Robbevalloire, R. Gras and J. Blouet

Institut Supérieur des Matériaux et de la Construction Mécanique, 3 Rue F. Hainaut, F-93407 St.-Ouen (France)

(Received April 8, 1992; revised and accepted July 2, 1992)

Abstract

The aim of the investigations was to improve the tribological properties of chromium oxide (Cr_2O_3) coating for applications in heat engines at high temperatures. The experimental results show that the solid lubricants CaF_2 and BaF_2 in composite coatings can reduce and stabilize the friction coefficient, decrease the wear rate, prevent surface damage and improve the load capacity of Cr_2O_3 coating at 425°C in air. In tribotests at 0.2–1.0 MPa it appears that the optimal solid lubricant content is around 14%–21% for Cr_2O_3 – CaF_2 coatings and 20%–31% for Cr_2O_3 – BaF_2 coatings. Auger electron spectroscopy and energy-dispersive spectroscopy analyses show that the friction coefficient is correlated with the amount of solid lubricant in contact areas: the friction coefficient decreases with solid lubricant content if it is less than 2%–4%, then stabilizes at about 0.20–0.25.

1. Introduction

Plasma-sprayed ceramic coatings such as zirconia and alumina have been applied to the combustion zone surfaces of different engines. They can ensure good thermal protection for components such as pistons, valves, upper liners, etc. The resulting improvements in engine durability and performance that have been experienced are significant and have led to increasing interest in the subject [1, 2]. However, the reduction in heat transfer resulting from the use of ceramic parts leads to a greater temperature rise in the cylinder walls of engines. These high temperatures, exceeding the cracking point of organic lubricants, generate dry sliding conditions between the liner and the piston ring [3]. In such cases the metallic parts cannot work because of their poor tribological properties under non-lubricated conditions at high temperatures. Consequently, an important task is to improve the tribological performance at high temperatures.

Ceramics, because of their good refractory properties, high hardness and good corrosion resistance, were considered as prospective candidate materials. Over a period of several years a large number of investigations have been carried out using different kinds of ceramics [4–8]. In comparison with metallic materials, ceramics have certainly improved the tribological performance, but the friction coefficient and wear rate of these materials are still too high for successful applications.

In order to improve the tribological properties of ceramics under severe sliding conditions, we have incorporated solid lubricants in the form of plasma-sprayed composite coatings [9]. The philosophy of these investigations is to exploit the high hardness of the ceramic matrix and the good properties of the solid lubricant.

The ceramic used in these studies is chromium oxide (Cr_2O_3). It was selected according to the results of our experimental investigations [10, 11]. The solid lubricants used are calcium difluoride (CaF_2) and barium difluoride (BaF_2). They are considered as having good thermal and chemical stabilization and a strong lubrication effect [12].

2. Experimental details

2.1. Materials

The commercial Cr_2O_3 powder used in these investigations has been produced by melting and crushing techniques. The experimental CaF_2 and BaF_2 powders have been developed by Rhône Poulenc; scanning electron microscopy (SEM) shows that both powders consist of angular and spongy particles. Table 1 presents some of their technical characteristics.

The composite coatings have been obtained by the atmospheric plasma spraying of powder mixtures on a mild carbon steel (35CD4) substrate that had been sand blasted with corundum. In order to improve the

TABLE 1. Technical characteristics of powders

Powder	Chemical composition (wt.%)	Powder description	Particle size (μm)
Cr_2O_3	94.97 Cr_2O_3 , 3 Fe, 1 Cr, 0.55 S, 0.45 Ca, 0.03 Mo		30-70
CaF_2	94 CaF_2 , 1.65 Si, 0.5 Mg, 0.09 Al, 0.03 Fe, 0.01 Mn, 0.01 Cu	Angular, spongy	70
BaF_2	96.91 BaF_2 , 0.33 Si, 0.01 Mg, 0.05 Al, 0.05 Fe, 0.93 Sr, 0.09 Ca, 0.335 O, 0.055 C	Angular, spongy	10

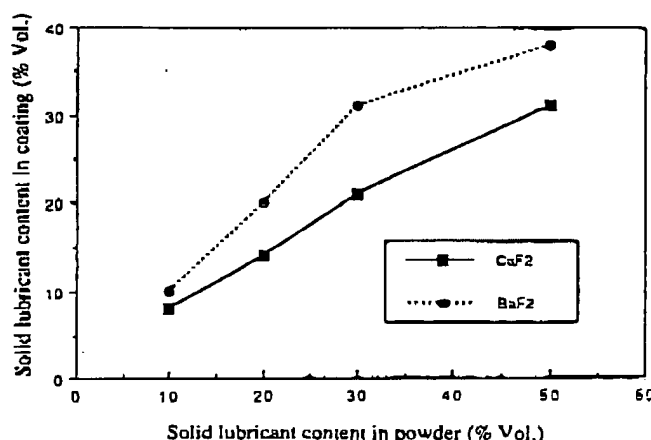
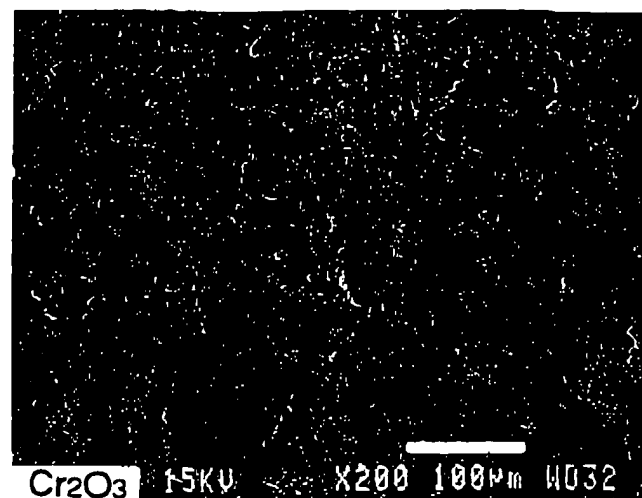


Fig. 1. Correlation between solid lubricant contents in powder mixtures and composite coatings.

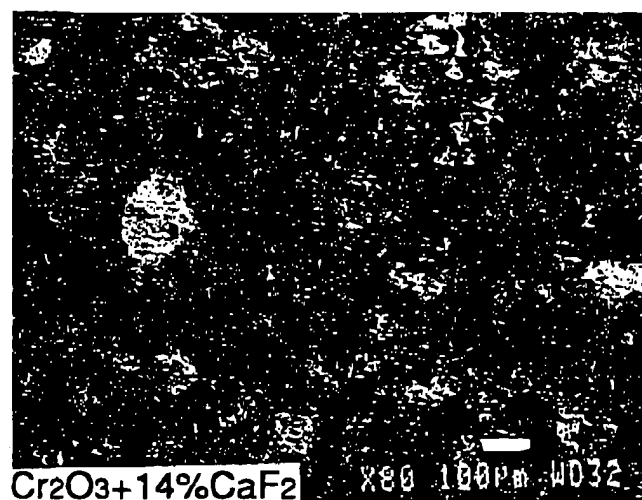
adherence of the coatings to the substrate, a bond coating of 80 μm depth of pure Cr_2O_3 was sprayed before deposition of the composite coating.

Chemical analysis shows that the solid lubricants are partially lost during spraying, especially for the Cr_2O_3 - CaF_2 coatings, mainly because of the difference in their fusion points, which results in different evaporation rates. Figure 1 shows the correlation between the solid lubricant content of the powder mixture and that of the composite coating. Generally, this loss will increase with increasing solid lubricant percentage: the solid lubricant content in the coatings varies from 8% to 34% CaF_2 for the Cr_2O_3 - CaF_2 coatings and from 10% to 38% BaF_2 for the Cr_2O_3 - BaF_2 coatings when the solid lubricant content in the powder mixture varies from 10% to 50%.

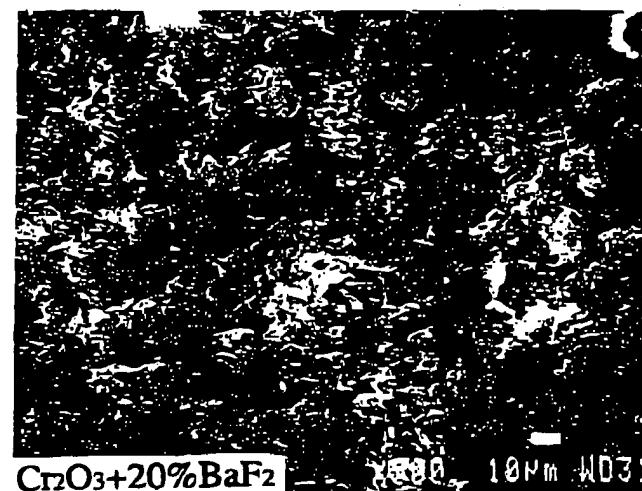
The coated surfaces have been observed by SEM. Some typical images are shown in Fig. 2. The composite coatings consist of a ceramic matrix (Cr_2O_3) and solid lubricant particles dispersed in the matrix. The particle size is generally about 10 μm , but some of them can be more than 100 μm . Their shape is spheroidal. On the surface of the coatings we have observed some open pores. Statistical analysis of the Cr_2O_3 - CaF_2 coatings shows that the porosity increases with increasing



(a)



(b)



(c)

Fig. 2. Initial microstructures of coatings: (a) Cr_2O_3 , (b) Cr_2O_3 -14% CaF_2 , (c) Cr_2O_3 -20% BaF_2 .

solid lubricant content. Consequently, the coating density decreases and the roughness of the ground surface of the composite coating increases with increasing solid lubricant content.

Before sliding, we measured the Vickers hardness of the polished cross-section and of sliding surfaces with different roughnesses; *i.e.* ground and polished sliding surfaces. Figure 3 presents the hardness results. Although there is some scatter among these measurements due to differences in the roughness and structure as well as in the nature of the solid lubricants, we have found that the hardness decreases with increasing solid lubricant content and that the hardness of the Cr_2O_3 - BaF_2 coatings is slightly lower than that of the Cr_2O_3 - CaF_2 coatings.

In order to minimize the influence of the surface roughness on the friction and wear of the coatings, the sliding surface was lightly polished with abrasive paper of mesh 1000# to obtain samples with the same R_a ($0.4 \mu\text{m}$ for the Cr_2O_3 coating and $0.6 \mu\text{m}$ for the Cr_2O_3 - CaF_2 and Cr_2O_3 - BaF_2 coatings). Before each test the samples were rinsed with denatured ethyl alcohol.

2.2. Apparatus and experimental conditions

All experiments were carried out using a tribometer specially designed for investigations of friction and wear in air at high temperatures [13, 14]. Its schematic description is given in Fig. 4. Rotation is provided by a spindle linked to an electric motor. Sliding occurs between two plasma-coated cylindrical ring surfaces of area 286 mm^2 which are mounted on a stationary and a rotary spindle respectively. Normal load is applied through the stationary spindle by dead-weights hung on the loading arm when the normal load required is small (less than 0.55 kN) and by a pneumatic system when the normal load is larger (0.55 – 6.5 kN). The samples are heated to the required temperature, as measured by the thermocouples, using an electric furnace. The stationary spindle is restricted by a torque-sensing system which measures the friction coefficient at high temperatures (20 – 1100°C). The friction force is recorded continuously.

All tests were carried out under the following conditions: environment, atmospheric air; temperature, 425°C ; sliding velocity, 0.1 m s^{-1} ; contact pressure, 0.1 – 22.1 MPa , corresponding to a normal load of 28.6 N– 6.32 kN .

The total sliding time for most experiments was 6 h . Damage processes were followed by optical microscopy and SEM, interrupting the motion after 0.5 , 2 and 4 h of sliding. Wear was characterized from the mass loss of both discs after taking into consideration the oxidation weight gain of the metallic substrate (see Appendix).

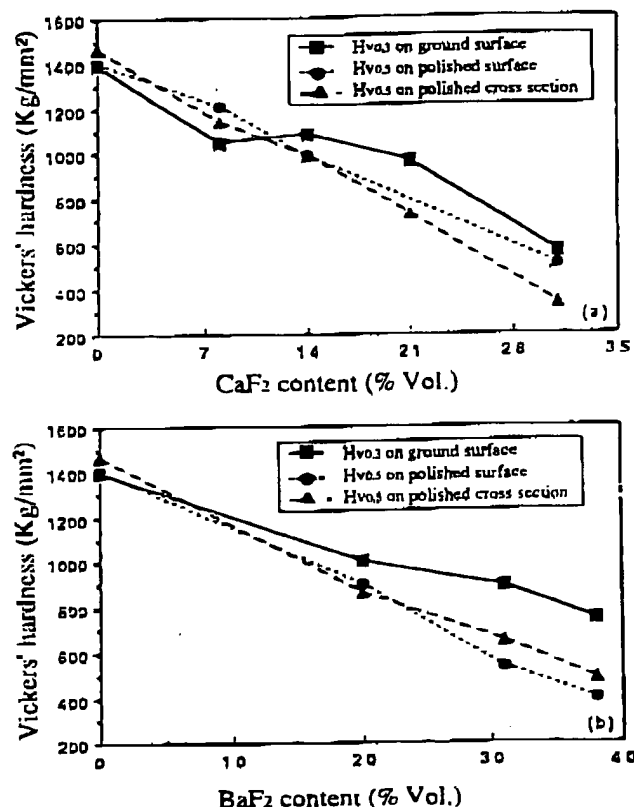


Fig. 3. Evolution of Vickers hardness of (a) Cr_2O_3 - CaF_2 and (b) Cr_2O_3 - BaF_2 with solid lubricant content.

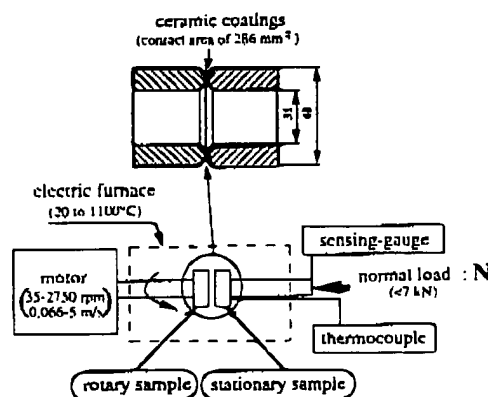


Fig. 4. Schematic operating principle of the tribometer.

3. Experimental results

Five friction couples – $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$, $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ - CaF_2 , Cr_2O_3 - $\text{CaF}_2/\text{Cr}_2\text{O}_3$ - CaF_2 , $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ - BaF_2 and Cr_2O_3 - $\text{BaF}_2/\text{Cr}_2\text{O}_3$ - BaF_2 – have been tested. The results will be presented in terms of the following three aspects:

- (1) improvement in tribological properties of Cr_2O_3 coating by solid lubricant addition;
- (2) influence of solid lubricant content, nature and distribution on friction coefficient and wear rate;

(3) tribological properties of the coatings under high pressure.

3.1. Improvement in tribological properties of Cr_2O_3 coating

Comparing the friction and wear of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ with those of the other couples, we find that the solid lubricants improve the tribological properties of the Cr_2O_3 coating. Figure 5 shows typical friction curves of tribotests carried out under the same conditions. Two observations can be derived from them. Firstly, for the friction of pure Cr_2O_3 , the stick-slip phenomenon occurs and a considerable variation in the friction coefficient is observed. When a solid lubricant is introduced in one or both coatings, the variation in the friction coefficient becomes much smaller and the stick-slip phenomenon disappears. Secondly, the mean friction coefficient without solid lubricant is about 0.4, but it is much smaller and varies between 0.2 and 0.25 if there is a solid lubricant in the coating(s).

Figure 6 presents the evolution of mass loss vs. sliding distance under a pressure of 0.2 MPa. It shows that this evolution can be distinguished by two different stages:

(1) At the beginning of a test the mass loss is significant. Microscopic observations show that this results from surface polishing, which produces considerable wear because of the removal of some sharp asperities. For the test under pressures between 0.2 and 1.0 MPa this stage is shorter than 30 min.

(2) After the running-in stage the wear of the coating becomes more stable and regular and the mass loss increases linearly. To evaluate the wear resistance of different coatings, we have used the "wear rate K_v " term, which is defined by the formula

$$K_v = \frac{\Delta m}{\rho P S V t}$$

where Δm is the mass loss of the two samples of one couple, ρ is the mean density of the coatings, P is the apparent pressure, S is the nominal contact area, V is the sliding velocity and t is the sliding time.

Table 2 presents wear rates and mean friction coefficients of different couples under pressures of 0.2, 0.5 and 1.0 MPa. It is seen that the solid lubricants can reduce the wear rate considerably.

Figure 7 presents photographs of the surfaces of Cr_2O_3 , Cr_2O_3 -14% CaF_2 and Cr_2O_3 -20% BaF_2 after 6 h of sliding under a pressure of 0.2 MPa against Cr_2O_3 . They show that the Cr_2O_3 surface after sliding against Cr_2O_3 has been damaged and is characterized by the removal of material in some contact areas with strong adhesion. However, when a solid lubricant is introduced in the coating(s), the surfaces of the samples made of Cr_2O_3 and Cr_2O_3 -solid lubricant become macroscopi-

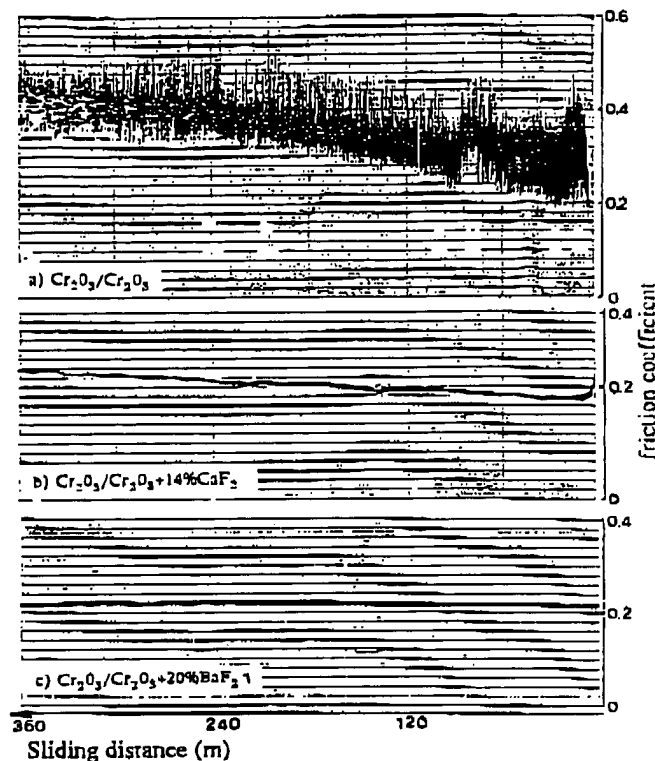


Fig. 5. Friction curves under 0.2 MPa.

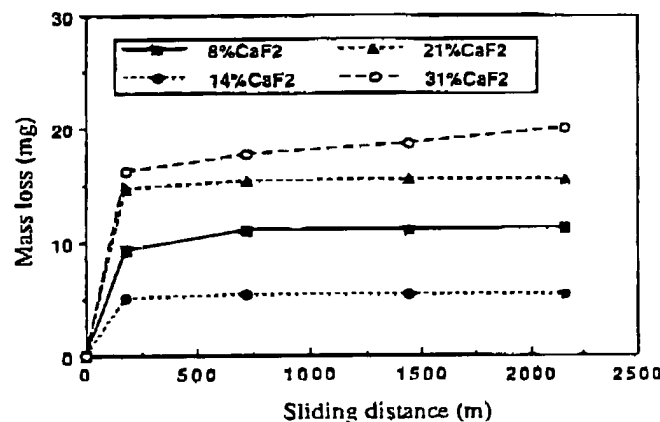


Fig. 6. Variation in mass loss with sliding distance for Cr_2O_3 - Cr_2O_3 - CaF_2 under 0.2 MPa.

cally very smooth, while microscopically they are characteristic of the formation of contact plateaux via plastic deformation; we have not observed any extensive surface damage.

3.2. Influence of solid lubricant content, nature and distribution

3.2.1. Influence of solid lubricant content

The solid lubricant content exerts an important influence on the tribological properties. Figure 8 presents the variations in friction coefficient and wear rate

TABLE 2. Mean friction coefficient f , friction coefficient dispersion amplitude Δf and wear rate K , under 0.2, 0.5 and 1.0 MPa

Friction materials ^a	Contact pressure (MPa)								
	0.2			0.5			1.0		
	f	Δf	K (10^{-6} mm^3 $\text{N}^{-1} \text{ m}^{-1}$)	f	Δf	K (10^{-6} mm^3 $\text{N}^{-1} \text{ m}^{-1}$)	f	Δf	K (10^{-6} mm^3 $\text{N}^{-1} \text{ m}^{-1}$)
$\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$	0.42	0.1	6.5	0.35	0.04	6.1	0.32	0.02	5.0
$\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -x%SL									
SL: CaF_2 x = 8	0.25	0.005	0.23	0.30	0.006	0.66	0.58	0.008	4.1
14	0.25	0.003	0.16	0.26	0.003	0.13	0.27	0.003	0.06
21	0.26	0.003	0.05	0.23	0.003	0.25	0.26	0.003	0.12
34	0.26	0.004	4.7	0.26	0.004	3.0	0.26	0.005	1.9
SL: BaF_2 x = 10	0.29	0.004	0.51	0.25	0.004	0.12	0.27	0.005	0.06
20	0.24	0.003	0.88	0.24	0.003	0.13	0.25	0.003	0.02
31	0.25	0.003	0.09	0.22	0.003	0.06	0.23	0.003	0.12
Cr_2O_3 -x%SL/ Cr_2O_3 -x%SL									
SL: CaF_2 x = 14	0.27	0.004	0.08	0.27	0.004	0.07	0.28	0.004	0.3
21	0.27	0.004	0.13						
34	0.27	0.004	5.6	0.26	0.004	1.7	0.25	0.004	2.7
SL: BaF_2 x = 20	0.27	0.003	0.09	0.27	0.003	0.09	0.27	0.003	0.03
31	0.26	0.003	0.08	0.25	0.003	0.07	0.27	0.003	0.06
38	0.26	0.003	0.85	0.24	0.003	0.12	0.23	0.003	0.62

^aSL, solid lubricant.

vs. CaF_2 content for friction of the $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ - CaF_2 couple, while Fig. 9 presents those for the Cr_2O_3 - $\text{BaF}_2/\text{Cr}_2\text{O}_3$ - BaF_2 test. They show that a low solid lubricant content generally produces a high friction coefficient and a substantial wear rate. On increasing the solid lubricant content, the friction coefficient first decreases and then stabilizes at about 0.2–0.25. However, we have observed optimal content ranges for the wear rate: 14%–21% CaF_2 for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ - CaF_2 sliding and 20%–31% BaF_2 for Cr_2O_3 - $\text{BaF}_2/\text{Cr}_2\text{O}_3$ - BaF_2 sliding. These phenomena can be explained by the different influences of the solid lubricant on the tribological and mechanical properties of the coatings: an increase in the solid lubricant percentage can certainly improve the tribological properties, but it also produces a degradation in the mechanical properties. This is the reason why coatings with a medium content of solid lubricant show the best performance.

3.2.2. Influence of solid lubricant nature

Figure 10 compares the friction coefficients and wear rates of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -x% CaF_2 sliding with those of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -x% BaF_2 (x is the solid lubricant content by volume in the powder mixtures). It shows that the sliding friction coefficient of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -x% BaF_2 is slightly lower than that of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -x% CaF_2 , while their wear rates show the same trend. This small difference between the two kinds of solid lubricant may

result from their different hardnesses, i.e. the hardness ratios of Cr_2O_3 and the solid lubricants will be different, which will result in a slightly different friction coefficient [15].

3.2.3. Influence of solid lubricant distribution

Figure 11 compares the friction coefficients and wear rates of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -x% CaF_2 sliding with those of Cr_2O_3 -x% $\text{CaF}_2/\text{Cr}_2\text{O}_3$ -x% CaF_2 (x is the solid lubricant content by volume in the coatings). Generally, $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -x% CaF_2 has a lower sliding friction coefficient than Cr_2O_3 -x% $\text{CaF}_2/\text{Cr}_2\text{O}_3$ -x% CaF_2 , while their wear rates are of the same magnitude. Similar phenomena have been observed in sliding with Cr_2O_3 -x% BaF_2 coatings. Figure 12 compares the friction coefficients and wear rates of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -x% BaF_2 sliding with those of Cr_2O_3 -x% $\text{BaF}_2/\text{Cr}_2\text{O}_3$ -x% BaF_2 (x is the solid lubricant content by volume in the coatings).

3.3. Tribological properties of the coatings under high pressure

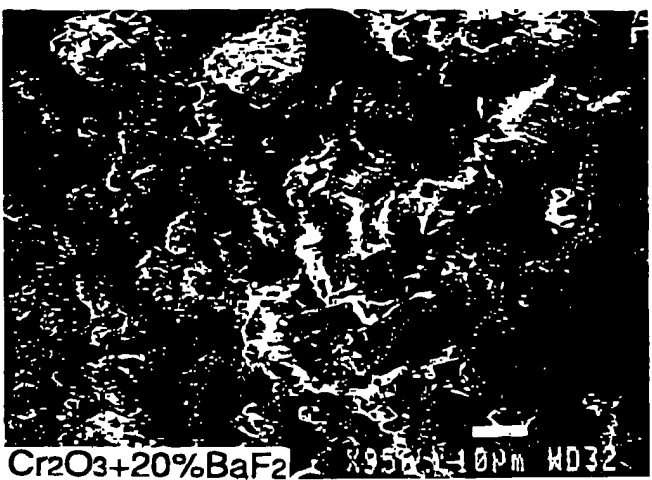
It is very important to determine the maximal pressure of the coatings for applications. For this purpose we have measured the friction coefficients and wear rates of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ and $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -14% CaF_2 sliding under high pressures up to 22.1 MPa and generally confirmed the reduction in friction coefficient and wear rate by solid lubricant addition even under high pressure.



(a)



(b)



(c)

Fig. 7. Surface damage of (a) Cr_2O_3 , (b) Cr_2O_3 -14% CaF_2 and (c) Cr_2O_3 -20% BaF_2 after 6 h of sliding against Cr_2O_3 under 0.2 MPa.

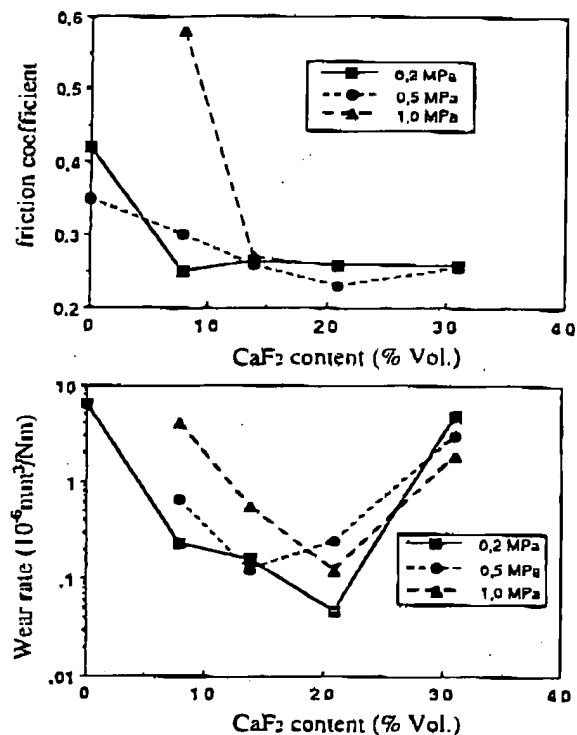


Fig. 8. Evolution of friction coefficient and wear rate of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ - CaF_2 with CaF_2 percentage.

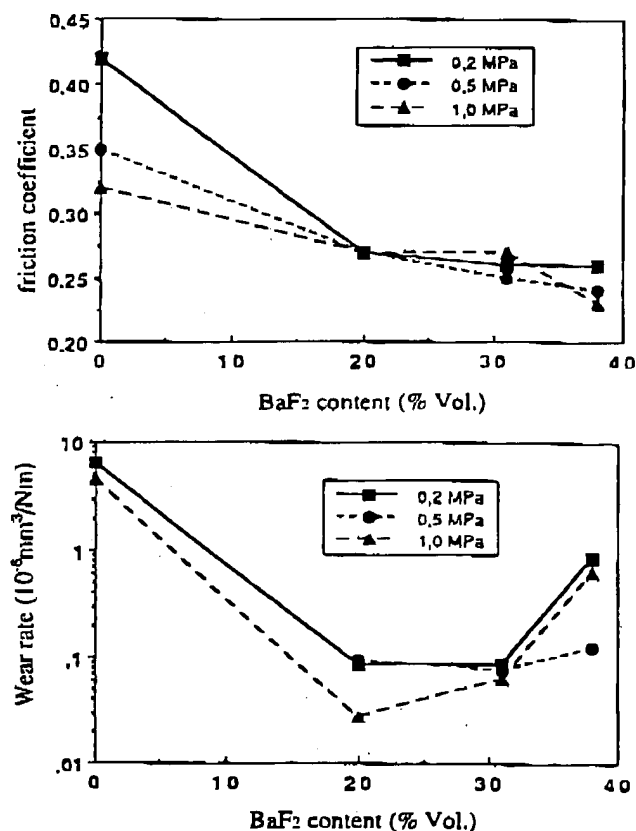


Fig. 9. Evolution of friction coefficient and wear rate of Cr_2O_3 - $\text{BaF}_2/\text{Cr}_2\text{O}_3$ - BaF_2 with BaF_2 percentage.

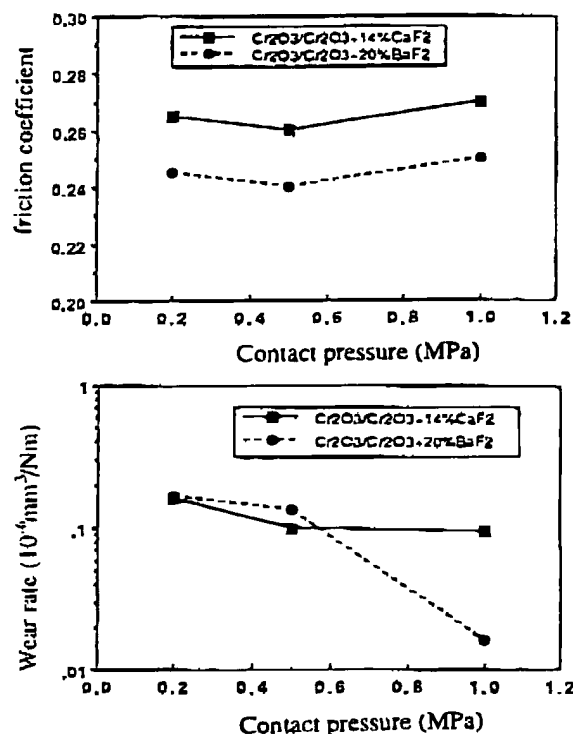


Fig. 10. Comparison of friction coefficient and wear rate of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3-14\%\text{CaF}_2$ and $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3-20\%\text{BaF}_2$ under 0.2 MPa.

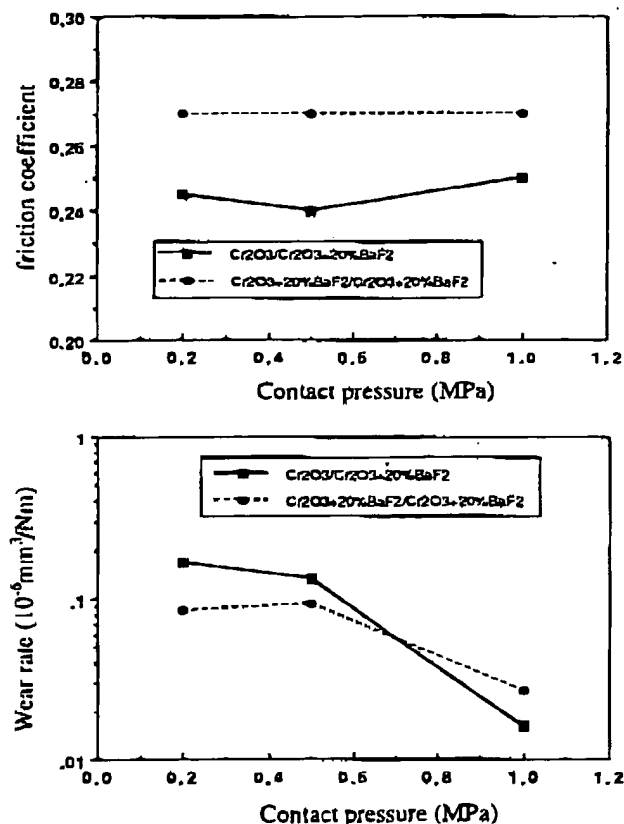


Fig. 12. Comparison of friction coefficient and wear rate of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3-20\%\text{BaF}_2$ and $\text{Cr}_2\text{O}_3-20\%\text{BaF}_2/\text{Cr}_2\text{O}_3-20\%\text{BaF}_2$.

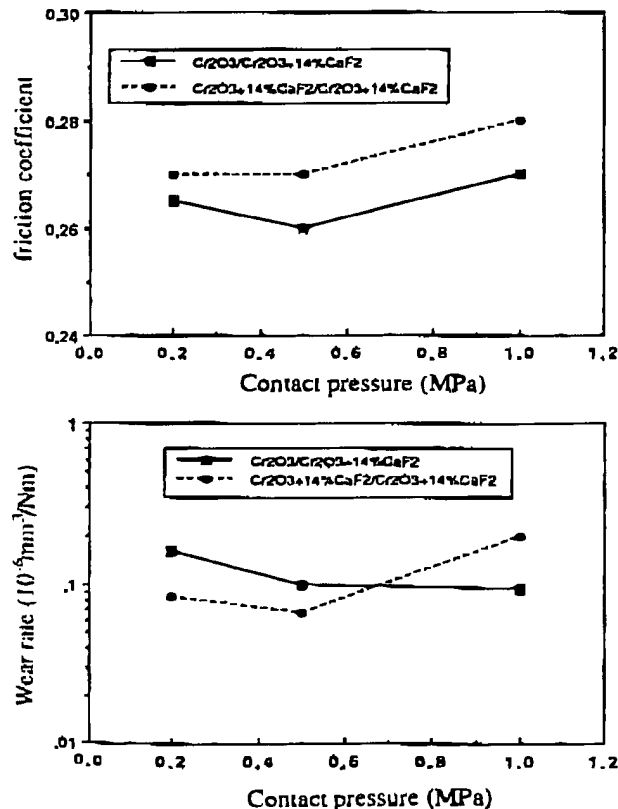


Fig. 11. Comparison of friction coefficient and wear rate of $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3-14\%\text{CaF}_2$ and $\text{Cr}_2\text{O}_3-14\%\text{CaF}_2/\text{Cr}_2\text{O}_3-14\%\text{CaF}_2$.

It is important to point out that although Cr_2O_3 -solid lubricant coatings are less hard than pure Cr_2O_3 coating, the increase in critical load achieved by using a solid lubricant in the tribological case is clearly evident: for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ sliding, chevron-shaped cracks have been observed under a pressure of 14.5 MPa; however, for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3-14\%\text{CaF}_2$ sliding, the cracking pressure increases from 14.5 (4.15) to 22.1 MPa (6.32 kN). This improvement in load capacity of the coating probably results from the reduction in friction coefficient brought about by the solid lubricant, i.e. the tangential load will decrease and consequently the critical load will obviously increase [16].

4. Characterization of the sliding surfaces and discussion

By use of Auger electron spectroscopy (AES) we have analysed the contact areas (contact plateaux) and non-contact areas of Cr_2O_3 and $\text{Cr}_2\text{O}_3-14\%\text{CaF}_2$ coating surfaces after 6 h of sliding. Figure 13 presents the results of a typical analysis of the Cr_2O_3 coating surface. We have found that the spectrum obtained in the contact area contains one calcium peak with a significant amplitude, whereas this peak does not exist in the non-

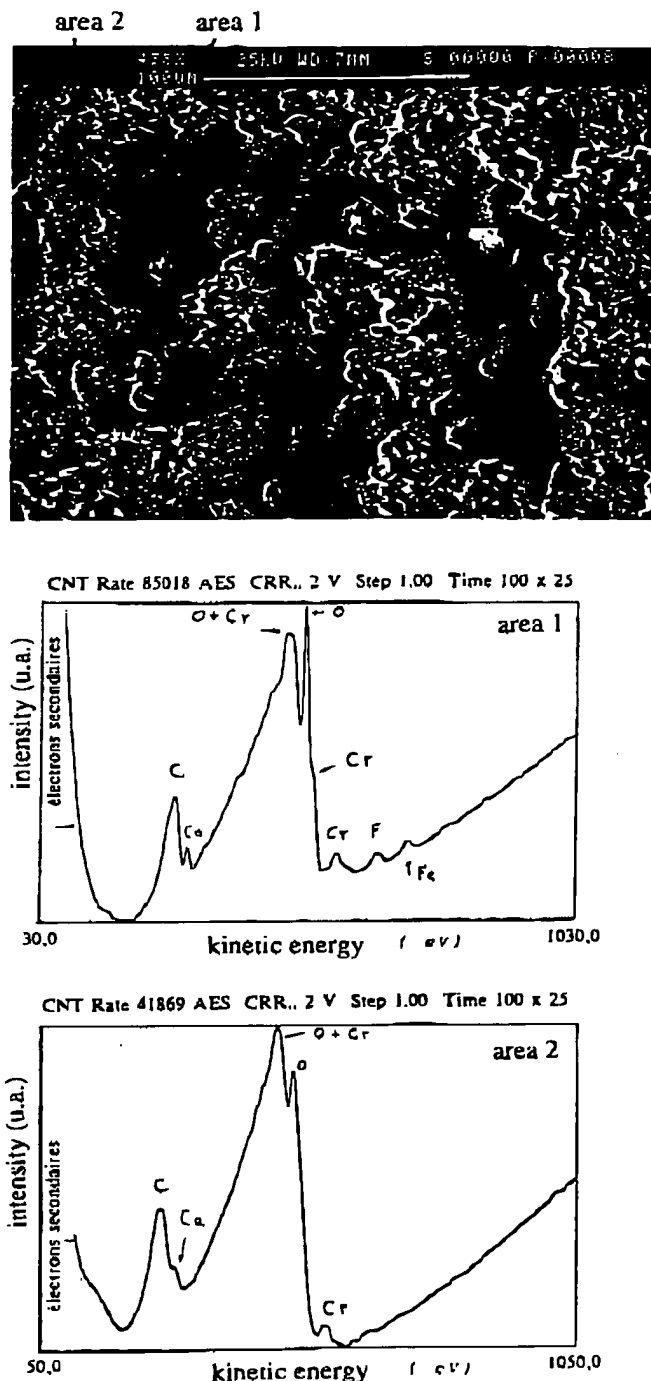


Fig. 13. Results of AES analysis of contact and non-contact areas on Cr_2O_3 surface after 6 h of sliding against Cr_2O_3 -14% CaF_2 under 0.2 MPa.

contact area. These analyses indicate that sliding can enrich the solid lubricant on the surface, thus inducing an improvement in friction and wear properties.

In order to confirm this idea, a large number of analyses by energy-dispersive spectroscopy (EDS) have been carried out on different worn specimens. Figure

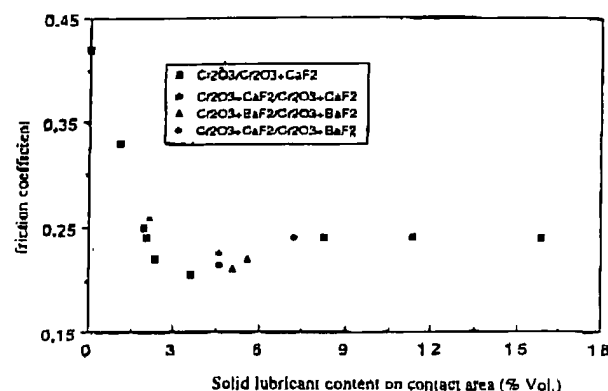


Fig. 14. Correlation between friction coefficient and solid lubricant (resulting from material transfer) content on contact area.

14 presents the relation between friction coefficient and mean solid lubricant content of three to five measurements on contact areas of various specimens. It shows that the friction coefficient first decreases with solid lubricant content if it is less than 2%–4% and then stabilizes at about 0.20–0.25 when the solid lubricant content is more than 4%. Thus the good friction and wear properties of the composite coatings probably result from the solid lubricants on contact areas producing two important effects:

- (1) a reduction in adhesion strength, which restricts the formation of adhesive junctions [11];
- (2) the presence of a soft superficial layer (CaF_2 or BaF_2) which reduces the proportion of shearing resistance at the yield point of the hard material (Cr_2O_3) [15].

5. Conclusions

(1) The tribological performance of Cr_2O_3 coating can be improved by the incorporation of solid lubricants (CaF_2 and BaF_2). The mean friction coefficient has been reduced from about 0.4 for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ sliding to 0.2–0.25 for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -solid lubricant sliding; the friction curve of the Cr_2O_3 coatings with solid lubricant becomes much more stable than that of pure Cr_2O_3 coating.

(2) Solid lubricant addition has also improved the wear resistance of Cr_2O_3 coating; the wear rate has been decreased from $6.5 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ sliding to about $10^{-8} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -solid lubricant sliding.

(3) The solid lubricant can improve the load capacity of Cr_2O_3 coating. The cracking pressure increases from 14.5 MPa (4.15 kN) for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ to 22.1 MPa (6.32 kN) for $\text{Cr}_2\text{O}_3/\text{Cr}_2\text{O}_3$ -14% CaF_2 .

(4) The optimal solid lubricant content is around 14%–21% for Cr_2O_3 - CaF_2 coatings and 20%–31% for Cr_2O_3 - BaF_2 coatings.

